Measurement of Energy Spectrum of High Intensity X-Ray Beams Using Compton Scattering (コンプトン散乱を用いた高強度X線ビームのエネルギースペクトルの測定)

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Recently X-rays are used in many fields like medicine, industry and so on. Most applications of X-ray are based on their ability to pass through matters. X-rays that have passed through a body provide a visual image of its interior structure when they strike a photographic plate or a fluorescent screen. Radiography by X-ray is very effective in medical diagnosis and nondestructive testing of products for defects.

In particular, radio diagnostic technologies are widely used in medical fields such as mammography and CT (computed tomography). The image quality and functions of these equipments are getting better rapidly owing to technology development such as high quality electron beam. At the same time, the radiation dose in these equipments approaches to the level that it should be monitored and managed appropriately against biological hazard. On the other hand, sufficient X-rays dose with specified energy spectrum is indispensable to achieve high quality image.

Therefore, control and assurance of the X-ray energy spectrum and the dose or fluence rate of these systems (quality control and quality assurance: QA & QC) are getting important more and more. For the purpose, we have to know the energy spectrum of primary X-ray and its intensity accurately. The information on energy spectrum is more important to apply the X-ray radiography to the advanced analysis using two X-rays with different spectrum (energy subtraction method etc). Generally, however, the X-ray energy spectrum is difficult to estimate only by the calculation because of lacks in the model, information on materials of target, filters and so on. Consequently, measurement is indispensable, and measurement should be done with good energy resolution because the spectrum consists of sharp peaks of characteristic X-rays and a continuous part.

In modern radiographic apparatuses like mammography and CT, as mentioned above, the X-ray beams are so intense that the direct measurement is impossible because of too much dead time or pile up, and furthermore, control of count rate by the distance or collimation is also impossible because of limited space in some devices.

To overcome the problem, developed was the Compton spectrometer in which primary photons are scattered with appropriate scatterer to 90-deg direction, and scattered photons are detected with intensity weaker by several decades. In this technique, the primary energy spectrum is derived using the Compton differential cross-section and geometrical information like solid angle etc. However, the energy resolution of Compton scattered spectrum is deteriorated mainly due to angular spread of the scattering angle, multiple scattering and the electron movement in the sample. It is affected also by the material and the shape of the scattering object. In the first generation of the Compton spectrometer, the efficiency was low to apply to the practical measurement. Therefore, it is important to study the optimum shape by optimizing the shape of scatterer and geometry to achieve the energy resolution and the efficiency as high as possible but have been performed only partially. Nowadays, computer simulation can be used as a very powerful tool to simulate such investigations. It is very worthwhile to make optimization of the Compton spectrometer aiming at better resolution and higher efficiency.

In relation with the purpose, full characterization of semiconductor γ-ray detector CdTe is also required because it is best suited for medical environment owing to the advantages of compactness, high efficiency and good energy resolution at room temperature.

Further, the measurements of X-ray spectrum in CT have been done only in a stationary mode i.e. the X-ray tube was held at one position in the gantry and not allowed to either rotate or move in the CT plane. For the measurements in operating condition, there is only a preliminary report. To confirm the validity of the measurement in one point, and also the reported position dependence of X-ray spectrum and dose rate in CT, development of a Compton spectrometer enabling the measurement in operating condition or similar condition will be required.

The aim of the present thesis is to develop a Compton spectrometer which is useful for the energy spectrum measurement in modern radiographic system with high intensity which enables measurement with high efficiency and good energy resolution, and further measurement in CT under operating condition.

The chapter one summarizes the background of the study, the present status of the research and the aim of the thesis.

In Chapter 2, I summarize the requirements for the Compton spectrometer, the design of the spectrometer, a γ-ray detector suitable to medical facility, and discuss about the features of scatterer and geometry.

A Schottky CdTe detector was selected for diagnostic X-ray measurements to meet the requirement that a X-ray detector has high energy resolution. Compactness of the detector is also necessary because of a limited space available in some X-ray units. CdTe detectors are much more compact than Hp-Ge detectors and offer sufficient photon detection efficiency, and to a great advantage they can be used at room temperature. Therefore they can be good candidates for X-ray spectroscopic systems. However, the energy resolution of the CdTe detectors may be deteriorated by the charge carrier trapping effect which reduces the photo-peak efficiency and causes a low energy tail structure in γ-ray peak area. Therefore, improvement of the analysis of carrier trapping phenomenon is important and studied in the thesis.

Scatterers of low atomic number are shown to give rise to small contributions of coherently scattered photons. On the other hand, scatterers of high atomic number produce energy broadening due to the Compton profile because the mean binding energy increases with the increasing atomic number. Therefore, the materials and geometry is important for realize good compromise of the efficiency and the energy resolution.

In Chapter 3, Characterization of CdTe and Compton spectrometer has been done. New analysis method is also proposed for carrier trapping effect.

The performance of the Schottky CdTe detector was evaluated for operating conditions, i.e., bias voltage and shaping time. From the detector response for an ^{241}Am source, it was found that higher full energy absorption efficiency and lowest tailing are achieved naturally at the highest bias voltage of 200 V and the optimum shaping time is around 2 μsec as a compromise between the energy resolution and the pile up effect, although the dependence is not so strong. In addition, the stability of the CdTe detector was confirmed for long term operation due to polarization around 24 hours for γ-ray spectrum of ^{241}Am.

Then the response function of the detector was simulated by the Monte Carlo code as the basis of data analysis. The charge carrier trapping effect in the detector was also studied because the past analysis could not reproduce the experimental results completely. In the present calculation, the carrier trapping effect was analyzed by newly taking account of the effect of non-uniform electric field in the detector. The introduction of the non-uniform electric field improved greatly the reproducibility of the calculation in the tail region of the response function for γ-ray spectra. The tailing part of the response function now can be simulated exactly based on the new method. Therefore, this method can be used also for other semiconductor detectors in which the carrier trapping effect is more serious.

To confirm the calculated response function of the Compton spectrometer, Compton scattered photon spectra were measured by the Schottky CdTe detector for mono-energetic primary beams in the range of 10-60 keV obtained by the synchrotron light source at KEK, Tsukuba. Agreement was very good over the incident energy region including the tail. In addition, the primary photon intensity derived from the measured response was in agreement with direct measurements with an ionization chamber. Therefore, the applicability of the Compton spectroscopy to obtain the incident photon spectra for intense X-ray fields was substantiated.

In Chapter 4, the way to obtain good compromise between the efficiency and the energy resolution was considered using thick scatter of carbon. For the purpose the factors which deteriorate the energy resolution were considered. Traditionally, the optimal scatterer shape has been considered to be a cylinder or circular rod (diameter less than 5 mm) lied in a scattering chamber of a Compton spectrometer but the efficiency was really low. A sample of cylinder with cutting angle was proposed but no detailed analysis was reported. Here, to find better solution based on the detailed simulation, computer simulation of Compton scattered photon spectrum was carried out using the MCNP4C code for different shape of thick scatterers, and then the primary spectra under a clinical operating condition were acquired using the Compton method with the schottky CdTe detector and two appropriate scatterers.

A carbon scatter considered was columnar one (2 cm-diam) whose surface is cut at various angle from 15-deg to 75- deg as well as cylindrical one (2 cm-diam). The axis of the scatter was set on the axis of the X-ray beam. The simulation provided the data of the energy spectrum of scattered photons for each scatterer.

The results of the simulation indicated that the scatterers with cutting angle of 15-deg and 30-deg, achieve much better energy resolution with a little loss of the efficiency compared with the cylindrical sample. It shows the importance of the shape and the geometry.

By using the columnar sample and the CdTe detector, measurement of energy spectrum in radiographic machine was carried out with good signal-to-background ratio. From the results, the spectrum of primary X-ray beam was reconstructed with sufficient energy resolution. Further the dose derived from the reconstructed spectrum was in agreement with the direct measurement with an ionization chamber. It can be concluded that the optimization of the scatterer and geometry is important for the Compton scattering measurements, and thick carbon scatterers can be used effectively to evaluate the performance of radio diagnostic systems with higher efficiency.

Chapter 5 describes the development of a Compton spectrometer for CT under operating condition. In designing the new spectrometer, the following requirements were imposed in addition to enabling the measurement under operating condition: 1) low backgrounds both for incident and scattered X-rays, 2) good energy resolution, 3) high detection efficiency to enable the measurement in limited experimental period. Besides, the length of the spectrometer was also limited from the viewpoint of mechanical design.

The measurement under operating condition without deteriorating the signal to background ratio was realized by introducing six collimator opening for the incident photons into the scatterer. Then, the shape of the scatterer was optimized following the considerations in Chap.4, considering the scatterer shape and the geometry relative to the rotating X-ray tube of CT unit and detector. The scatterer should be axially symmetric to accept X-rays from six collimators distributed over 2π solid angle. Then, the scatterer shapes are limited to sphere, rod and cone. The sample shape was selected by optimization of the efficiency and the energy resolution. For the purpose, the sample was characterized with a volume V, and scattered photon spectrum was simulated to study the energy broadening for the given V. From the point of compromise between the efficiency and the energy resolution, the sample shape was made to be a cone of 355 mm^3.

The new Compton spectrometer was applied to obtain incident X-ray spectrum of CT unit under operating condition with a good signal-to-background ratio. The reconstructed spectra from the Compton spectrometer was validated through the agreement of exposures derived from the reconstructed spectrum with that by direct measurement using an ion chamber. Measurement in center and off center position of gantry indicated difference in the spectrum and dose. Therefore, it will be worthwhile to develop similar experiment to obtain more information in the X-ray field in CT.

In summary, the present thesis proposed a new means to design the Compton spectrometer to measure intense X-ray spectrum in medical field with good energy resolution and acceptable efficiency by considering the sample shape and geometrical conditions. Further, a method enabling the measurement of CT X-ray spectrum under operating condition and a new method to analyze the carrier trapping effect were proposed. The method will provide useful tools to develop quality control and quality assurance, and also research in various situations in medical X-ray fields.

論文審査結果の要旨

現在 X 線ビームは様々な分野で用いられ，医療分野においてはマンモグラフィや CT(コンピューティッドトモグラィ)装置など先端医療機器に不可欠である。機器の高度化とともに放射線量が増加し，画質に必要な所定のエネルギー分布と強度に関する品質制御と保証が重要な課題となっている。そのため装置における X 線スペクトルと線量を精度良く知ることが必要で，異なるエネルギースペクトルのビームを利用するエネルギー差分法などの高度な手法においてはさらに重要である。

しかし，通常 X 線装置のエネルギースペクトルを計算のみで評価することは困難であり，測定が不可欠である。これらの装置では，X 線ビームの強度が極めて強くかつ装置や装置室の条件から直接測定が困難であるため，X 線ビームを散乱させて強度を下げる Compton 散乱法が必要となる。従来の Compton 散乱法では効率が低く，エネルギー分解能を保持しつつ効率を高めることが重要であるが，十分な研究がなされていない。また，X 線 CT の運転(回転)状態で使用可能なスペクトロメータに関しても予備的な報告しかない。

本論文は X 線検出器として CdTe 半導体検出器を用いた高性能 Compton スペクトロメータの開発に関するもので，全 6 章からなる。

1 章は序論であり，本研究の背景と目的を述べている。

2 章では Compton スペクトロメータに要求される条件を整理し，医療施設に適した検出器として小型・高感度・高分解能の CdTe 検出器を選定し，効率とエネルギー分解能の両立を図るための条件を検討し，散乱体と幾何学的条件の適正化を図ることの重要性を指摘している。

3 章ではデータ解析の基礎となる CdTe 検出器と Compton スペクトロメータの応答関数を線源及び放射光による単色光を用いて測定するとともに，分散低減法を取入れたモンテカルロ法によって詳細計算を行いほぼ計算によって再現できることを検証している。単色光に対する応答関数は初めてのデータであり，計算で再現できることを実証した意義は大きい。また，キャリアトラッピング効果の解析に検出器内電界の不均一性を取入れることによってほぼ完全に再現できることを示している。これは他の半導体検出器への応用も可能な有用な成果である。

4章では，Compton スペクトロメータのエネルギー分解能の要因を分析し，エネルギー分解能低下の主要因である散乱角度の広がりを抑えつつ，散乱体原子数を増加させて効率向上を測る手法を具体化している。様々な形状の散乱体について，散乱スペクトルをモンテカルロ法で詳細に求め，散乱体形状とエネルギー分解能および効率との関係をシミュレーションで求めることを可能とし，同等の効率でエネルギー分解能を高める手法を提案している。これは広く応用が可能な重要な成果である。

5章では，X 線 CT の運転状態での測定を可能とするべく遮蔽型 Compton スペクトロメータを改良し，実働条件で低バックグラウンド・高分解能のデータを取得し，電離箱測定との比較で妥当性を確認している。また，位置によってスペクトルと線量が異なることを見出しており，X 線 CT の高度化への基礎情報を与えることが期待される。

5章はまとめであり，本研究の成果を総括している。

以上，要するに本論文は高強度 X 線ビームのための Compton スペクトロメータの高度化に関する研究をまとめたもので量子エネルギー工学に貢献するところ少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。